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Parameterization of single scattering properties of mid-latitude cirrus clouds for fast radiative transfer models using particle mixtures

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[1] A new parameterization of single scattering properties has been developed for mid latitude cirrus clouds for application to weather prediction and global circulation models. Ice clouds are treated as a mixture of ice crystals with various habits. The bulk optical properties of ice crystals are parameterized as functions of the effective dimension (D_e) of measured particle size distributions that are representative of mid latitude cirrus clouds. D_e is itself parameterized as a function of temperature and ice water content. The paper describes the results obtained with a stand-alone version of the radiation routine of the COSMO model and preliminary tests with the full forecast model in various meteorological situations characterized by extended high cirrus clouds over Europe. **Citation:** Bozzo, A., T. Maestri, R. Rizzi, and E. Tosi (2008), Parameterization of single scattering properties of mid-latitude cirrus clouds for fast radiative transfer models using particle mixtures, *Geophys. Res. Lett.*, 35, L16809, doi:10.1029/2008GL034695.

1. Introduction

[2] State-of-the-art Numerical Weather Prediction models (NWP-m) require fast radiative transfer schemes that can reproduce accurately the interaction between radiation and matter in the atmosphere and at the surface. The interaction between radiation and clouds has a strong impact on a number of processes, such as the surface energy balance and the diabatic heating within the atmosphere, and these processes, in turn, interact with other components of the NWP-m.

[3] Climate models are closely related to NWP-m; however the reciprocal influence between radiation and clouds is even more important since processes like the loss of energy to space are fundamental, while being of lesser importance for NWP-m.

[4] The radiative role of cirrus clouds is not well known because of our limited understanding of the relationship between the bulk radiative properties of ice clouds [Stephens *et al.*, 1990] and the size and shape of ice crystals, as well as the relationship of these with the atmospheric environment [Edwards *et al.*, 2007]. It is known that treatment of ice particle size and habit may have a significant impact on climate change [Kristjánsson *et al.*, 2000].

[5] We present a new parameterization of the radiative properties of cirrus clouds for a mixture of four most common ice crystal habits observed in mid latitude (ML) cirrus clouds [Heymsfield *et al.*, 2002; Lawson *et al.*, 2006].

In the first section of this paper, the single scattering properties of particle size distributions (PSD), composed of mixed shapes, are computed from the single-scattering properties of various ice crystal habits. In the second section bulk radiative properties of the mixed-shape PSD are parameterized as a function of the effective dimension (D_e). Since most of the NWP-m do not provide any microphysical information about ice crystals' size, D_e is parameterized as a function of temperature and ice content. Finally the new parameterization is inserted in the COSMO limited area model, developed by the Consortium for Small scale Modeling [Doms and Schaettler, 2001]. The third section summarises the preliminary results of sensitivity tests performed with a stand-alone version of the COSMO radiation routine and using the full forecast model.

2. Ice Crystal Mixture and Its Radiative Properties

[6] Based on a classification of shape versus size distribution, Lawson *et al.* [2006] identify three major size ranges in ML cirrus PSD. Spheroid-type particles provide most of the PSD's mass for the small particle range (size below 30 microns); the medium particle range, with size between 30 and 200 microns, is composed mainly of irregular crystals; rosette-shaped ice crystals fill the large particle range, with size larger than 200 microns. Finally a low percentage of hexagonal columns is observed, accounting for only 5% of the mass, mainly in the size range from 25 to 100–200 microns. The mass percentage distribution of the four habits that defines the mixture used in the present paper is presented in Figure 1 (left). The size range from 2 to 9500 microns is divided into a number of bins and for each bin the relative number concentration is computed from the mass concentration and the geometrical properties of each habit.

[7] Realistic PSDs, associated (cloud) layer temperatures (T) and ice content (IWC), are obtained from a database of 891 theoretical modified gamma-type distributions, fitted on observations. Data were collected in ML cirrus clouds during three measurements campaigns: FIRE I, FIRE II and ARM [Baum *et al.*, 2005; Heymsfield *et al.*, 2004]. This database will be denoted as PTI.

[8] The shape of a PSD modulates the contribution of each size bin, and hence of the habits, to total mass. Plotting the mass percentage of each habit for all the 891 PSDs versus T , for four temperature bins, as in Figure 1 (right), shows a relationship between the relative abundance of each habit type and T that is in good agreement with Lawson *et al.* [2006]. Therefore, for a given mixture of ML ice clouds (e.g., using what shown in Figure 1), the PSDs in the PTI

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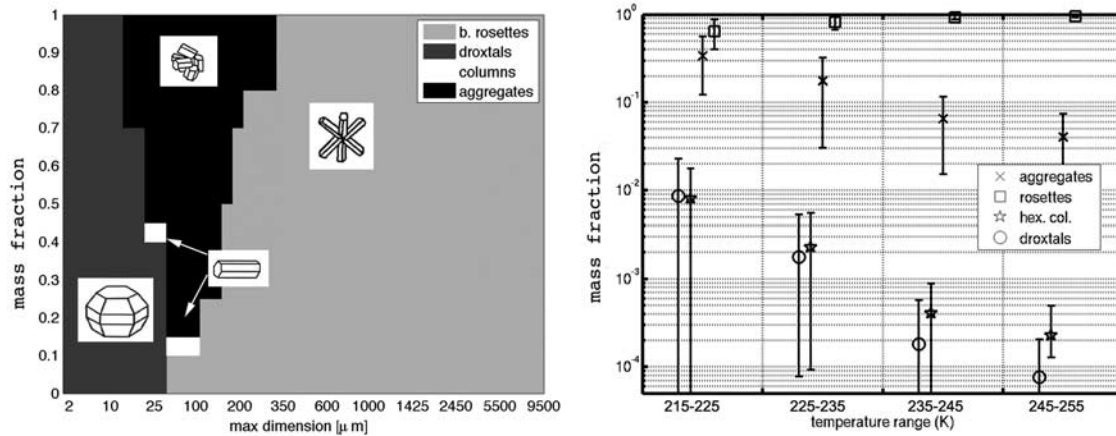


Figure 1. (left) Relative mass percentage versus size (maximum dimension) for the mixture adopted to describe mid-latitude cirrus clouds micro-physics. (right) Mass percentage of each ice habit used in the mixture versus cloud temperature for all the PSD in database PTI. Data are grouped in 4 T ranges. Error bars denote the spread of the available data (one standard deviation). The data are separated inside the T ranges for clarity.

database transform the shape-size relation into a shape-temperature dependence.

[9] The single scattering properties for different ice habits in the short-wave (0.25–4.5 microns) and long-wave (4.5–100 microns) spectral ranges are taken from *Yang et al.* [2005] and *Wyser and Yang* [1998]. The particles defined for the three size ranges mentioned above are simulated as follows: the small spheroid-shaped crystals using droxtal optical properties; the medium sized irregular crystals using random aggregates of hexagonal columns which represent the closest available choice; the large generic rosette-shaped particles using pristine (six branch) bullet rosette, which are the closest choice. The single scattering properties of the mixture are obtained, in each size bin, by the appropriate weighted sum of the properties of the various components [Liou, 1988, pp. 142–144]. The shape-temperature dependence outlined above implies that the optical properties of the mixture, which change both with the particle's size and habit, will possess an intrinsic dependency on layer temperature.

3. Bulk Optical Properties Parameterization Applied to the COSMO LAM

[10] COSMO is a non-hydrostatic LAM developed by the joint efforts of the meteorological services of Germany, Switzerland, Italy, Greece and Poland [Doms and Schaettler, 2001, 1999]. The radiation scheme uses the delta-two stream formulation of the atmospheric radiative transfer equation [Zdunkowski et al., 1980], adapted by Ritter and Geleyn [1992]. It describes cloud radiative properties in terms of the single scattering albedo (ω), the asymmetry parameter (g) and the mass extinction coefficient (k). The radiative properties of ice clouds are modelled after *Rockel et al.* [1991], indicated as RAL in what follows, and are based on the treatment of the ice particles as spheres with optical properties parameterized as function of IWC .

[11] At the moment no cloud microphysical information is provided to the radiation routine in COSMO, the interface being limited to the IWC and T of the atmospheric layer. The

optical properties of the mixture, however, depend mainly on the D_e of the PSD, defined as [Baum et al., 2005]

$$D_e = \frac{3}{2} \frac{\sum_{h=1}^4 \left[\int_{D_{\min}}^{D_{\max}} V_h(D) n(h, D) dD \right]}{\sum_{h=1}^4 \left[\int_{D_{\min}}^{D_{\max}} A_h(D) n(h, D) dD \right]} \quad (1)$$

where V_h and A_h are respectively the volume and the projected area of the h -th habit and $n(h, D)$ is the number concentration of the h -th habit in the size bin of maximum dimension D .

[12] A relationship between D_e and (T , IWC) can be extracted from the PTI database. D_e is found to obey to a two-variable fit, following the equation:

$$D_e = c_0 + c_1 T + c_2 \log_{10}(IWC) + c_3 T^2 + c_4 [\log_{10}(IWC)]^2 \quad (2)$$

A direct comparison with other parameterizations found in literature is often difficult due to the different PSD used in various papers, the different integration limits in the D_e computation, the various habits considered and different definitions of the average size.

[13] *Wyser* [1998] presents a relationship between the effective radius (R_e) and T and IWC , denoted as WYS in what follows, which is to be used with hexagonal crystals, therefore not easily comparable to the current parameterization (MIX). The factor defined by Wyser is used to convert R_e values to D_e . Moreover, as stated by *Wyser* [1998], the integration limits in the computation of D_e have a not-trivial impact and, in particular, the exclusion of the smallest particles may lead to serious, positive bias in the D_e computation. In fact ice crystals of a few microns have a large impact on radiative transfer simulations, especially in the solar range, since their contribution to scattering is amplified by their number, despite the limited contribution to total mass. In Wyser's work the integration limit for small

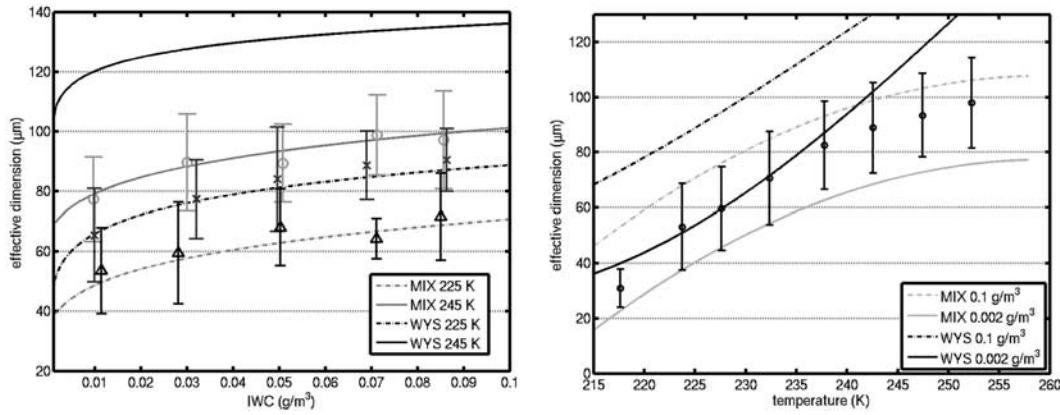


Figure 2. (left) D_e versus IWC derived from the PTI database and from the parameterizations. Gray lines denote the MIX parameterization and black lines the WYS parameterization for the two temperatures indicated in the legend. The symbols with error bars represent the average D_e values in five sub-intervals of width 0.02 g/m^3 from 0 to 0.1 g/m^3 , plotted versus the average IWC in same sub-interval. Data are presented for 3 temperature ranges: circles denote the average D_e values for the range 250–240 K, crosses same for 240–230 K and triangles for 230–220 K). The error bars represent one standard deviation and define the spread of the PTI data inside each IWC interval. (right) D_e as function of T derived from the PTI database and from the parameterizations. Grey lines are the MIX parameterization and black lines the WYS parameterization, computed for the two IWC values indicated in the legend. These IWC values are close to the high and the low extremes in the PTI database, in order to highlight the link between the spread of the data in each temperature interval and the IWC variability. The symbols with error bars represent the average D_e values in eight temperature intervals, from 210 K to 255 K. The width of the first interval is 10 K (210–220 K), while the width of the other seven intervals is 5 K. The error bars represent one standard deviation and define the spread of the D_e values inside each temperature interval for all IWC values contained in the PTI database. These spread estimates rely on more than 100 experimental point, except the first interval that contains only four experimental values. In fact the average $\underline{D_e}$ value in the first interval is included only to show the coverage available from the PTI database.

particles in D_e computations is set to 10 microns while in our work particles down to 2 microns are included. As shown in Figure 2 WYS and MIX have a similar dependence of D_e on IWC , while the dependence on T in WYS produces larger values due to the different volume/area ratio of hexagonal columns with respect to bullet rosette, which are the predominant habit in the present parameterization.

[14] COSMO's radiation scheme computes fluxes in 8 broad spectral bands. The high resolution optical properties of the mixture must therefore be spectrally averaged taking into account, by some form of weighting, the energy available in each spectral band. The application of the simple weighted spectral-average of mass extinction coefficient and single scattering albedo causes a mishandling of saturation effects [Ritter and Geleyn, 1992]. Therefore spectrally-averaged transmittances are computed through an ensemble of path-lengths, representative of the typical layer thickness in the COSMO model and of available cirrus cloud climatology [Liou, 1992]. The mean single scattering albedo and extinction coefficients are retrieved from these. The relationship between g , ω , k and D_e is obtained with a functional dependence similar to that employed by Fu [1996] and Fu et al. [1998]:

$$\begin{aligned} g &= a_0 + a_1 D_e + a_2 D_e^2 + a_3 D_e^3 \\ \omega &= b_0 + b_1 D_e + b_2 D_e^2 + b_3 D_e^3 \\ k &= c_0 + c_1 \frac{1}{D_e} + c_2 \frac{1}{D_e^2} \end{aligned} \quad (3)$$

where the mass extinction coefficient (k) is in m^2/kg and a_x , b_x , c_x are the constants to be determined for each of the 8 spectral bands.

4. Implementation in COSMO LAM: Preliminary Sensitivity Tests

[15] A series of experiments have been performed with a stand-alone version of the COSMO radiative scheme, as a first step in the implementation of the new parameterization into the COSMO model. Homogeneous cloud layers have been inserted in different standard atmospheric profiles [McClatchey et al., 1972] at different altitudes and solar zenith angles.

[16] Figure 3 (top) shows the results in terms of the ratio of broadband SW (as defined within COSMO) up-welling to down-welling flux at cloud top, representative of broad band cloud albedo. Figure 3 (bottom) shows the difference between the net LW flux at cloud top and net LW flux at cloud bottom, representative of net LW cloud absorption. These quantities are computed using RAL and our mixture approach (MIX) for various IWC for a ML Summer profile with solar zenith angle set to 35 degrees.

[17] MIX shows a higher SW albedo (Figure 3 (top)) than RAL for a cloud temperature of 220 K, whereas in warmer cloud layers smaller differences are found between the two parameterizations (not shown). Cold cloud layers appear to be highly sensitive to small temperature perturbations. In Figure 3 (top) the sensitivity of the broad band SW albedo to small changes ($\pm 5 \text{ K}$) in the mean cloud layer temperature

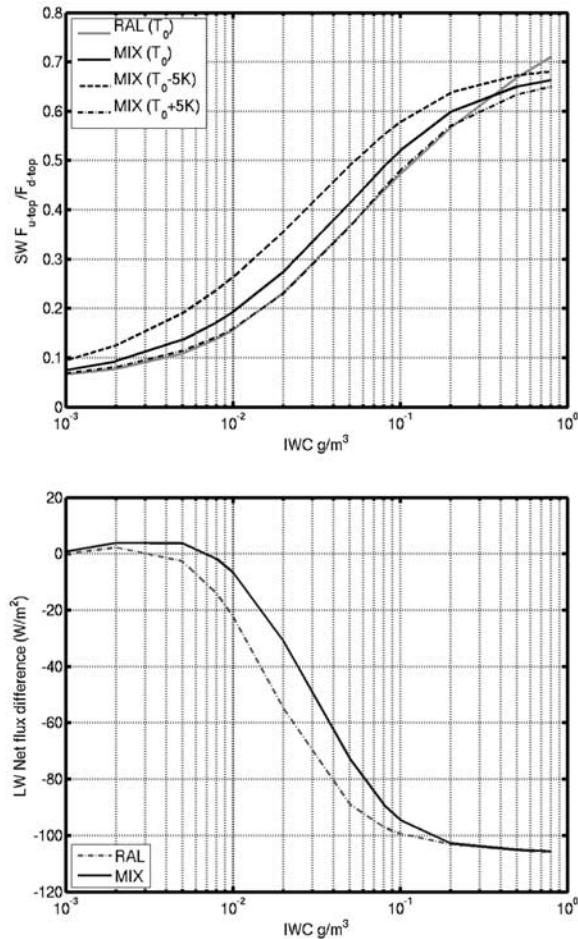


Figure 3. (top) SW albedo versus IWC using MIX (black line) and RAL (gray line). The sensitivity to a change in layer temperature is shown for MIX: the black dashed/dashed-dotted line is for an increment of T_0 by -5 and $+5$ K. (bottom) LW net flux (flux at cloud top minus flux at cloud bottom) versus IWC using MIX (black line) and RAL (gray dashed line). For both panels the computations are done for the Standard Mid Latitude Summer atmospheric profile. Cloud top is at 13 km, cloud thickness 1.7 km, cloud mean temperature 222 K and solar zenith angle is 35° .

of 220 K is shown. MIX is more reflective for colder temperatures (dashed line), whereas warming the layers (dashed-dotted line) brings to results comparable to RAL. Low sensitivity to temperature perturbations is found for temperature higher than 230 K (not shown), since warmer cloud layers are characterized by a larger amount of big crystals and are not affected by small changes in the medium and small particle's mode of the PSD. A lower net LW flux absorption is obtained with MIX (Figure 3 (bottom)): largest differences are found in warmer cirrus layers and for IWC around $10^{-2} g/m^2$ (not shown).

[18] Preliminary tests using the COSMO model show sensitivity to the change in radiative properties of ice clouds. Several short case studies, characterized by extended high cirrus clouds, have been examined. LW and SW fluxes associated to these extended patches of high ice clouds show mainly a reduction of both the incoming SW and LW radiation at the ground, due to an increase of optical

thickness in the SW and a reduction of LW absorption and emission. The differences in 2m temperature between the MIX run and the control run (that uses RAL) show extended negative temperature biases of 0.5–1 K associated to the MIX run in the region of maximum persistence of cirrus layers. The effects on cloud dynamics and hence on the evolution of cloud systems are subjects of ongoing investigations as well.

5. Conclusions

[19] The main purpose of this work is to present a new treatment of radiative properties for mid-latitude (ML) cirrus clouds to be used in fast radiative transfer codes for numerical weather prediction and global circulation models. A ML cirrus cloud is assumed to be a mixture of spheroid-type, irregular crystals, rosette-shaped crystals and hexagonal columns. A database representative of measured Particle Size Distributions (PSD) of ML cirrus clouds is used as a realistic description of PSDs, temperature and ice content.

[20] Once the mixture is defined, the shape of the PSD modulates the contribution of each size bin, and therefore the relative abundance of each habit type to total mass, as function of cloud temperature and ice content. Therefore the size-shape dependence of the mixture is implicitly linked to a temperature-shape relationship.

[21] The single scattering optical properties of ice clouds are computed for such a mixture between 2 and 9500 microns. These properties are parameterized as function of the effective dimension (D_e) of the PSDs and adapted to the COSMO-LAM's broad spectral bands. Since some NWP models do not provide information about the D_e of the ice crystals, a relation between D_e and T and IWC is determined from a database of measured PSDs [Baum *et al.*, 2005; Heymsfield *et al.*, 2004].

[22] Tests have been conducted with a stand-alone version of the radiation routine of the COSMO model comparing the new parameterization (MIX) with the current version [Rockel *et al.*, 1991] (RAL). MIX clouds show lower LW net flux absorption than RAL and show strong temperature dependence of SW radiative properties for high, cold clouds (temperatures below 230 K). An initial test using the COSMO model in a complex meteorological situation over Europe shows systematic biases, with respect to the control run, for 2m temperature, SW and LW fluxes from the very early stages of the integration. Impacts on cloud dynamics are also observed.

[23] As soon as some information on the microphysical composition of ice crystals in tropical high clouds will be available, the proposed methodology can be easily adapted to work in a global domain. At that point it will be possible to perform global sensitivity tests over long integration times.

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